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Multipurpose characterization of glazing systems with silica aerogel: In-field experimental analysis of thermal-energy, lighting and acoustic performance

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ABSTRACT

Thermal-energy, acoustic and lighting performance of innovative glazing systems with aerogel inclusion is evaluated through in-field experiments. The study is carried out by monitoring two dedicated prototype buildings located in central Italy, and the consistency of results with in-lab analyses is investigated. Analyses showed that aerogel can decrease energy consumption for heating by up to 50% in winter, and its capability to keep the thermal zone warmer even several days after that the heating system is switched off. Acoustic analyses confirmed in-lab measurements, showing aerogel capability to increase the façade acoustic insulation index by 3 dB. Lighting analyses showed aerogel effect to lower the daily average illuminance level by about 10% during sunny days. In cloudy weather conditions, with low level of solar radiation and indoor illuminance, the effect was relatively higher. In those cases when windows include shading elements such as protruding roof or deep window pad, aerogel effect was not clearly identified through continuous monitoring. The results of this integrated in-field experimental campaign showed that aerogel filled glazing cameras represent effective and innovative solutions for energy saving in winter, useful for improving acoustic façade performance with limited penalties in terms of daylighting.

1. Introduction

Energy consumption in buildings corresponds to 20–40% of total energy required, and it overcomes both industry and transportation sectors in EU and US [1]. Additionally, it has grown in the last few years because of the increasing expectation of indoor thermal comfort conditions by users [2,3]. This same increase in energy consumption, together with the rise in fuel price and in the attention against CO_{2eq} emissions, pushed research and design interest toward the development of new materials and technologies for optimizing building energy performance [4]. Moreover, the techniques aimed at investigating such performance, e.g. building monitoring, in lab experiments, dynamic simulation [5–9] have become increasingly reliable and advanced tools. In fact, they allow to take into account the overall realistic weather and indoor–outdoor boundary conditions [10,11], such as occupancy schedules, inter-building surrounding [12–14], which represent important key factors for the optimal choice of materials and technologies for new constructions and retrofit interventions [15]. Materials for opaque and transparent envelope in green buildings should be chosen depending on the real boundary conditions and occupancy characteristics in dynamic regime [16]. This acknowledged result of previous research contributions [17,18] led the research development toward the analysis of building envelope performance and its optimization through continuous monitoring experiments [19,20]. In fact, these experiments allow to characterize the thermal-energy behavior of full-scale building prototypes and real buildings. In particular, these systems were used to investigate, for instance, the role of insulation in building envelope, the impact of reflective coatings and cool applications [21], the effect of innovative materials such as phase change materials (PCMs). In particular, Soubdhan et al. [21] evaluated four different roof constructions under tropical climate, for several insulation typologies, in order to define the best performing solution in this weather conditions. Olivieri et al. [22] assessed the yearly thermal performance of green roof system with varying roof ventilation, by monitoring surface temperatures and thermal fluxes through the roof in summer and winter conditions. Long-term duration monitoring was carried out by Pisello and Cotana [9], in order to evaluate the effect of

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innovative cool clay tiles in a residential building located in temperate climate area. De Gracia et al. [23] proposed a new experimental equipment designed to study the thermal performance of PCMs in building façade, in both transient and stationary regime. Another important experimental study was carried out by Bontemps et al. in Ref. [24], where a passive solar test-room was built and monitored with an internal hollow glass bricks wall with PCM inclusions. A PASSYS test cell was also used by Assimakopoulos et al. [25] in order to investigate the performance of electrochromic window with varying control strategy.

Important research contributions also focused on the role of windows as fundamental envelope component. It represents, in general, the weakest part of the envelope insulation system [26,27], which is able to impact visual, acoustic and thermal comfort conditions, and energy requirement for lighting, cooling, and heating. Important results have been achieved in order to investigate innovative strategies aimed at optimizing windows' performance. In this field, new materials have been incorporated into the window systems, such as electrocromic glazing [25], movable solar shields [26], silica aerogel superinsulating glazings [27,28]. In particular, given the promising findings of numerical and experimental in-lab characterization of translucent aerogels, these systems have been manufacturing since the nineties. They have been mainly used to fill the camera between two glass (or polycarbonate) layers, with the purpose to achieve high-performance daylighting systems, e.g. polycarbonate panels, structural panels for curtain walls, and insulated glasses for windows. In this view, Duer and Svendsen (1998) [28] presented the main results of a key European research project, being the purpose to evaluate benefits and penalties of monolithic aerogel glazings. In this study the authors reported the main measurements of thermal and optical properties of prototypical evacuated aerogel double glazed units. Then, Schultz and Jensen [29] evaluated the thermal-energy performance of evacuated aerogel glazings, with particular attention to the evacuation and assembling process. Additionally, Jensen et al. [30] studied the heat loss coefficient and the solar transmittance of several prototypes of aerogel sheets developed during the HILIT European project. Nevertheless, advanced glazing systems with monolithic aerogel have still not penetrated the market and this technology is still currently under evaluation due to the difficulty to produce large monoliths of high optical quality. For these reasons, nowadays the building's applications focus on glazing systems with granular aerogels.

Important developments of the research around granular aerogels for energy efficiency applications in buildings were presented by Reim et al. in Ref. [31]. In this work the authors measured the heat transfer coefficients and the solar energy transmittance of granular silica aerogel glazing panels with thickness less than 5 mm. Interesting applications are also in evacuated solar collectors, for its capability to reduce the thickness of conventional flat-plate collectors and to decrease the heat loss by about 40% [31]. The optimization of the implementation procedures was also carried out in Ref. [31] where the authors proposed to mount aerogel granules in sandwich structures, i.e. between PMMA panels. The results showed an optimization of both thermal and optical properties for promising applications in solar walls. Buratti et al. [32] performed an in-lab campaign on aluminum frame window prototype with nano-porous silica granular aerogel in glazing interspace. Experimental results showed good acoustic properties and excellent thermal performance, i.e. thermal transmittance of the innovative glazing system was decreased by 1 W/m^2 K with only 15 mm of granular aerogel between two glass layers. In fact, aerogel windows were found to have an important role in improving both thermal performance and daylight in fenestration industry, because of very low conductivity, high acoustic insulation and light transmission, and low weight [33]. Other innovative window systems concern Vacuum Insulation Panels (VIP), which have a thermal conductivity of the same order of aerogel, but still very high cost and some technical limits as they have to keep the glazing gastight [34,35].

Table 1
Characteristics of transparent (A) and opaque (B) envelope components of the test-rooms.

A. Transparent envelope element [44]	Reference window [NO-AEROGEL Glazing]	Prototype window [AEROGEL Glazing]
External glass layer	Low-e glass (4 mm, magnetronic low-e coating on side 2)	Low-e glass (4 mm, magnetronic low-e coating on side 2)
Interspace	Air (15 mm)	Granular Aerogel (15 mm)
Internal glass layer	Float glass (4 mm)	Float glass (4 mm)
Total thickness [mm]	23	23
Thermal transmittance U	1.56 W/m^2 K	1.09 W/m^2 K

B. Opaque envelope element		Thermal transmittance
Test-Room 1_External wall		
1 Brickwork, outer leaf	Thickness: 0.12 m	0.29 W/m^2 K
2 Plasterboard	0.01 m	
3EPS insulation	0.09 m	
4 Brickwork, inner leaf	0.25 m	
5 Gypsum plastering	0.02 m	
Test-Room 2_External wall		
1 Plaster dense	Thickness: 0.02 m	0.29 W/m^2 K
2 EPS insulation	0.09 m	
3 Brickwork, inner leaf	0.30 m	
4 Gypsum plastering	0.02 m	
Test-Room 1_Roof		
1 Clay tile	Thickness: 0.015 m	0.25 W/m^2 K
2 Mineral wool insulation	0.015 m	
3 Air gap (ventilation layer)	0.05 m	
4 Mineral wool insulation	0.08 m	
5 Aerated concrete slab	0.20 m	
5 Gypsum plastering	0.015 m	
Test-Room 2_Roof		
1 Bitumen sheet	Thickness: 0.01 m	0.25 W/m^2 K
2 Mineral wool insulation	0.10 m	
5 Aerated concrete slab	0.20 m	
5 Gypsum plastering	0.015 m	
Test-Room 1 and Test-Room 2_Ground floor		
1 Linoleum	Thickness: 0.004 m	0.30 W/m^2 K
2 Glass fiber slab	0.10 m	
5 Cast concrete	0.30 m	

An important field experiment about granular aerogel insulation of glazing systems is carried out by Dowson et al. (2011) [36] who tested a 10 mm thick prototype polycarbonate panel filled with granular aerogel. Two prototypes with 6 mm and 10 mm of aerogel thickness were included in a test window, attached to the internal face of the frame using duct tape. A 15-mm air gap was created between the panels and the existing glazing. In situ U-values of the prototypes and the control panel were calculated, by measuring external and internal temperatures. The light transmission was also measured by lux sensors in the centre of each panel. Very significant reduction (80%) in heat loss with respect to single glazing was achieved by designing a purpose built retrofit solution containing aerogel, with acceptable reduction in light transmission.

From the previous findings about properties of monolithic and granular aerogel window system through in-lab and in-field characterization, the main original contribution of this research consists of the in-field experimental integrated analysis of aerogel glazing system in full-scale prototype buildings. The multipurpose analysis